Modeling Plastic Instability and Strain Localization in Explosively Driven U6 Hemi

Q. Ken Zuo and Paul J. Maudlin (T-3), and Lawrence M. Hull (DX-3)

Straining localization refers to the formation of a highly localized deformation in the form of thin planar bands (of the order of 10 μm) as the result of material softening, which occurs when the material becomes plastically unstable. Tensile tests of uranium alloyed with 6% niobium (U6) show stable behavior in the as-received condition but unstable behavior at very modest strain level in the post-shocked condition. The post-shock condition refers to the material properties after being processed by a large amplitude shock wave, as is the situation when a shell is accelerated by in-contact explosives. Hemispheres filled with explosives are used here to test our ability to predict the onset of plastic instability in expanding U6 shells. The ultimate goal is to develop the ability to predict the onset of instability, the dynamics of the unstable motion, the fracture of the shell into individual fragments, and the size and spatial distribution of the fragments and fragmentation debris.

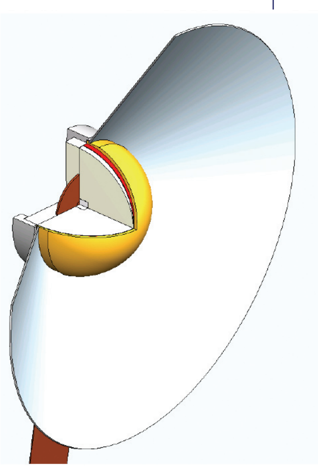

Figure 1— Schematic of the filled hemisphere experiment.

The filled hemi consists of a hemispherical U6 shell filled with explosive (PBX 9501) and initiated at the center (Fig. 1, see [1] for a detailed description of the test setup). A series of experiments has been conducted using filled hemispherical shells (with the thickness of 1-2 mm) and applying various diagnostics. Radiographs and fragment recovery provide experimental information on the onset of material instability. Proton radiographs (pRad) are taken normal to the pole of the hemi at a sequence of times, and the images are shown in Fig. 2. It is observed that localized thinning occurs at early time (8.2 μs), and at later time these localizations coalesce into the ultimate fragmentation pattern. Fragment recovery experiments using a water medium have also yielded significant information on the behavior of the filled-hemisphere geometry. In the recovery experiments, the shell is immersed in the water initially so that there is no metal/water impact process that could induce additional material damage. The recovered fragments represent an approximation to the conditions at the time fragmentation is complete (the fragments are fully separated, as in the 16.8 μs radiograph).

Pre-shot computations were conducted to model one such experiment using EPIC, a 3D, explicit, finite-element code for large strain, high strain rate dynamic applications. The computational study focused on the effect of a large amplitude shock on U6 material in the dynamic response of the hemi, in particular, the prediction of the onset of material instability. Figures 3 and 4 are the snapshots of plastic strain distribution in the shell at 5 μs after the detonation wave hits the shell (which corresponds to about 8 μs in the pRad images), for U6 with two different processing conditions, i.e., as-received and shock-hardened, respectively. Figure 3 shows a relatively uniform deformation (the equivalent plastic strain ranges from 0.5 to 0.75), a typical result of a stable material, while Fig. 4 shows pronounced strain localization (the plastic strain reaches 1.00 in several cells while most of the hemi has a strain of about 0.6), resulting from the unstable material behavior of the shock-processed U6. Since the deformation remains stable and symmetrical (about the horizontal axis) for the as-received material, only a 2D cut (in the R-Z plane) is shown. For the shocked-processed material (Fig. 4), the expansion is initially axisymmetric, while the material is still stable but quickly loses the axisymmetry and becomes 3D as the instability develops.

The numerical results are consistent with our understanding of material instability and strain localization, namely, the critical strain at which material loses stability increases with the hardening modulus (the slope on the stress-strain curve) and decreases with the yield stress. The main effects of pre-shock on U6 are to raise the initial yield point and to significantly reduce the hardening modulus.

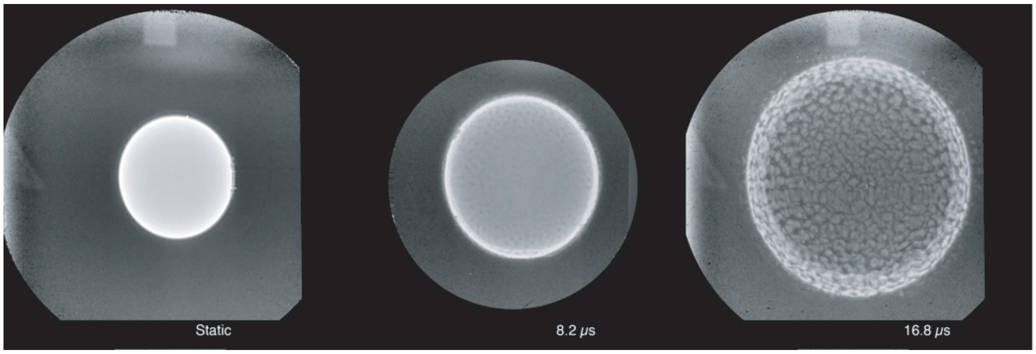

Figure 2—
Proton radiographs of the expansion of a filled hemi.

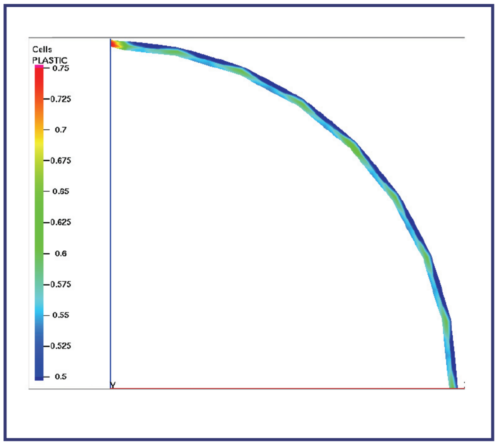

Figure 3—
Calculation of as-received U6.

Consequently, the shock-hardened U6 becomes unstable shortly after the detonation wave hits the shell and the shell expands nonuniformly while the calculation of the as-received U6 remains stable during the expansion. The experimental data supports the computations qualitatively and to some degree quantitatively. At 8 μs, localization is evident in the experiment as thinning in small spots. The recovered fragments show background strain of about 60%, and this compares well to the calculated background strain at 8 μs. The comparison of the background strain in the recovered fragments to the calculated strain at 8 μs requires the assumption that once localization begins, all the subsequent strain is concentrated in the localizations. In other words, the background strain ceases to increase when localization commences. The validity of this assumption remains to be checked. There is also at present no method of seeding the localization on a physical basis, so detailed comparisons of the experimentally determined spatial distribution of the thinned regions will not be expected to accurately match the calculated distribution.

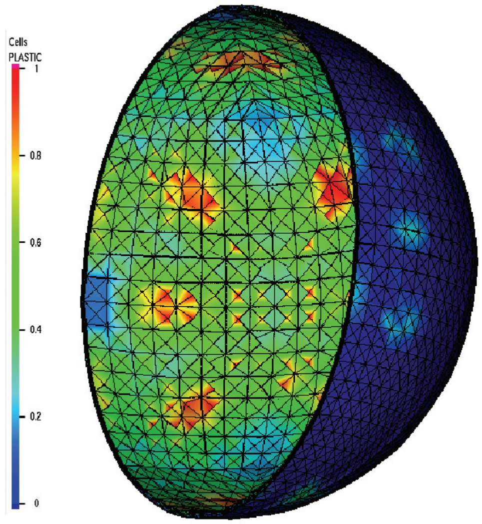

Figure 4—
Calculation of shock-hardened U6.

This summary is a part of a more comprehensive article on modeling deformation and damage of metals under high-rate loadings [1].

[1] G.T. Gray, P.J. Maudlin, L.M. Hull, Q.K. Zuo, and S.R. Chen, “Predicting Material Strength, Damage, and Failure-The Synergy Between Experiments and Modeling,” *Los Alamos Science* **29**, 80–93 (2005).

For more information, contact Q. Ken Zuo (zuo@lanl.gov).

Acknowledgements
We would like to acknowledge NNSA’s Advanced Simulation and Computing (ASC), Materials and Physics Program; and the Joint DoD/DOE Munitions Technology Development Program, for financial support.

Los Alamos
NATIONAL LABORATORY
EST. 1943